CAPACITIVE STRESS TRANSDUCERS IN MODEL DIPOLE MAGNETS

An Honors Fellows Thesis

by

CHRISTOPHER PETE BENSON

Submitted to the Honors Programs Office
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH FELLOW

April 2010

Major Subject: Physics

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Approved by:

Research Advisor:	Peter McIntyre
Associate Director of the Honors Program Office:	Dave A. Louis

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ABSTRACT

Capacitive Stress Transducers in Model Dipole Magnets. (April 2010)

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Capacitive stress transducers are used to measure mechanical stresses in the windings of superconducting dipole magnets. These transducers consist of a bonded laminate composed of alternating foils of stainless steel and a high-strength polymer known as polyimide. The thin, flat design of the transducers is ideal for measuring the integrated Lorentz stresses within the windings when current is flowing in the coil to generate a magnetic field.

The process of fabricating and calibrating these custom gauges has proven to be a non-trivial problem. Previously, many variables have been left unchecked during the fabrication and calibration phases thus leading to non-repeatable transducers.

My goal is to improve upon current methods of transducer fabrication to yield more consistent responses and robust packages. To accomplish this, new techniques and

fixtures have been developed to control factors, such as layer alignment, thickness variability and calibration consistency. New fixtures that have been developed are a polyimide cutting fixture, a new transducer alignment and epoxy curing fixture, a torque fixture, and a re-machined testing fixture. These new fixtures, coupled with new techniques, will increase the repeatability and reliability of the transducers.

Incorporating these fixtures has lead to a 75% decrease in thickness variations across the length of the transducers, 62% reduction in total epoxy thickness and a 70% decrease in number of pressure cycles required for calibration curve convergence. While these improvements produce impressive results, additional transducers are being constructed and calibrated to verify these findings. The improved fabrication and calibration methods and fixtures, results and conclusions will be discussed.

DEDICATION

For Mom and Dad

ACKNOWLEDGEMENTS

I thank Andrew Jaisle for the vast amount of time he spent helping with this project. Without his broad knowledge base, patience, experience and input, none of this would have been possible.

I also thank Dr. Peter McIntyre for allowing me to take on this project and inviting me to be a part of the Accelerator Technology Group. He has made this wonderful opportunity possible. A special thanks also goes out to Dr. Al McIntruff for sharing his knowledge of previous problems encountered during transducer production. Without his invaluable input and suggestions, I would have surely wondered astray. I also thank Trey Holik for the hours he assisted throughout this project. His help and suggestions helped move this project forward.

I thank Blake Ragland for providing me a strong foundation on which I could continue research on transducers. His fixtures and suggestions have been vital to pointing me in the correct direction.

I would also like to thank the rest of the group: Dr. Akhdiyor Sattarov, Tim Elliot, Raymond Blackburn, Kyle Damborsky, Nate Pogue, David Rahmani, John Cesar and Elizabeth Sooby for all of their help and making this such a positive experience.

Finally, I thank my family and Chelsey for their patience, encouragement and support this past year and a half. I am unable to express how thankful I am for their support.

NOMENCLATURE

C	Capacitance
nF	Nano-farad
MPa	Mega-Pascal
P	Pressure
pF	Pico-Farad
psi	Pounds per square inch

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CHAPTER I

INTRODUCTION

A driving goal behind research in accelerator dipole magnet technology is to increase future particle accelerator collision energies. This is done by increasing the magnet's maximum magnetic field. Increasing the magnetic field means higher particle velocities, i.e. kinetic energy, without having to increase the collier radius. However, a major challenge in building a high-field accelerator magnet is the effective management of induced Lorentz stresses. Because these are stresses near the limit of modern engineering materials, (150 MPa) care is be taken to ensure these forces are properly controlled [1].

Capacitive pressure transducers can be used to measure large stresses over wide temperature ranges. They are small in size and are ideal for places with limited space. In our magnets, capacitive stress transducers are the ideal choice because space is premium and they must endure temperatures from room temperature to cryogenic (4K) while being exposed to magnetic fields on the order of 10 Tesla [2].

Although the inner workings of capacitive stress transducers are relatively simple, fabricating and calibrating a series of repeatable and reliable transducers is an altogether non-trivial matter. Earlier research, performed by Blake Ragland, attempted to address

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This thesis follows the style of *IEEE Transactions on Applied Superconductivity*.

problems such as pin holes and layer misalignment by developing new texturing and epoxy/alignment curing fixtures. While the texturing fixture successfully eliminated pin holes in the polyimide layers while providing a uniform surface texture, the alignment and epoxy curing fixture did not provide sufficient control of epoxy thickness, layer alignment and pressure uniformity needed during the epoxy curing cycle. This caused differences from transducer to transducer which decreased the repeatability.

My goal is to take further steps towards developing repeatable and reliable transducers. To accomplish this, I incorporate the research findings of Ragland while introducing new fixtures to control variables that were previously unchecked. In the end, a fully developed and document fabrication and calibration procedure will be developed for future transducer production.

Fixtures

To solve several of the key issues above, I propose many new fixtures. These fixtures allow for more consistent and controlled transducer fabrication and calibration processes.

Polyimide cutting fixture

The purpose of a polyimide cutting fixture is to ensure a clean cut along the length of the polyimide layers. Previously, two templates sandwiched the polyimide while a razor cut it to required dimensions. While cutting along the length of the polyimide layers, tearing would often occur if the razor blade was not held at a certain angle. This is unacceptable because tearing opens up the possibility of shorting to occur along between two stainless steel layers along the edges of the transducers. To alleviate this problem, a cutting fixture allows the razor to cut in a more natural position rather than scraping along the face of the templates. This gives a clean initial cut without the risk of the razor catching the polyimide and causing tearing.

Newly designed alignment and epoxy curing fixture

The old alignment and epoxy curing fixture had many issues. Because it only consisted of two pieces, which slid over one another parallel to the surface containing the freshly assembled transducer during assembly, one was often guessing whether or not the freshly assembled polyimide and stainless layers had been misaligned once the fixture was assembled and clamped. The new alignment and epoxy curing fixture takes all guessing out of the picture. It contains two guide rails for the top piece to follow when being placed onto the transducer package. This will prevent any transverse sliding which could misalign the polyimide and stainless steel layers.

An additional feature the new alignment and epoxy curing fixture houses is its ability to bend the transducer leads 90 degrees once the package is clamped securely. This is accomplished by two additional attachments that can be guided and bolted in place once the leads are bent to specification.

The previous alignment and epoxy curing fixture used clamps to secure the fixture which did not evenly distribute the load or allow for consistent pressure. This fixture is clamped using a torque wrench to tighten 4 evenly spaced bolts along the length of the fixture. This allows for uniform clamping pressure. It is also important to mention that we have improved the dimensional tolerances at the location where the transducer is assembled to +/- 0.001”/0.000”. All of these improvements will work together to produce unprecedented transducer thickness uniformity.

Torque fixture

A torque fixture is required to provide a rigid support to hold the alignment and epoxy curing fixture while the torque wrench tightens the bolts. If epoxy curing fixture is not held rigidly in place, the actual tightening force will not be consistent because the fixture is slightly free to rotate. This will cause uneven pressure distribution on the freshly assembled transducer which in turn causes non-uniform thickness. Incorporation of the torque fixture will allows for total control during tightening.

Re-machined testing fixture

Steps have been taken to ensure the calibration is as consistent as possible. A test fixture used by Ragland has been re-machined to provide a flat testing surface. Because this fixture will hold the transducers during calibration in a press, each surface have been ground to tight tolerances to ensure that the transducer does not experience any point loading.

Calibration

To verify transducer repeatability, the calibration process must accurately reveal the behavior of the gauge. The main goal of calibration is to relate capacitance to applied pressure. This process is not straightforward because the calibration curves must converge before the behavior is stable. The convergence rates vary according to how well layer alignment and epoxy thickness were controlled during the fabrication process. It is ideal for convergence to occur within the least amount of cycles possible. However, this convergence rate needs to be reproducible.

Besides understanding the relationship between capacitance and stress on the transducer, the calibration process will also investigate a problematic zero offset. Zero offsets result from a magnet epoxy curing cycle that the transducers must endure once installed in the magnet. These zero offsets have been unpredictable and erase all previous pressure training. We hope increasing the repeatability of the transducers will yield a consistent zero offset. This will give a better idea where the zero offset has shifted the calibration curves once it is time to recalibrate the installed transducers following the magnet's epoxy curing cycle.

CHAPTER II

METHODS

The inner workings of capacitive stress transducers are fairly simple. Alternating foils of bonded stainless steel and a high-strength polymer, known as polyimide, form a simple multilayered parallel plate capacitor. Our transducers contain five 0.001” thick stainless steel electrodes, five 0.001” thick polyimide layers, and two outer .002” polyimide layers. The purpose of a multilayered package allows for a larger overall surface area, which increases the instrument’s sensitivity. As pressure is applied, the polyimide is compressed which decreases the distance between the stainless steel layers. This increases the capacitance. Following calibration, one can directly relate the measured capacitance to the pressure on the transducer.

Constructing and calibrating custom capacitive transducers requires many steps with attention to sensitive details. Each step is fully described below.

Fabrication

There are several steps in the fabrication stage. These are described in this section.

Polyimide and stainless steel texturing

Before the polyimide and stainless steel are cut to size, their surfaces are textured. This is done to ensure a strong epoxy bond once the package is assembled. This is similar to sanding a car before painting so the paint may have a rough surface to properly bond to. Similarly, the polyimide and stainless steel layers must be textured so the epoxy may properly bond to the surfaces. A texturing fixture, developed by Blake Ragland, is used in this step. Shown in Fig. 1, the texturing fixture runs the polyimide and stainless between two semi-circles covered by sandpaper. The distance between the sandpaper semi-circles may be carefully controlled using two dial indicators. This allows for uniform texturing across the surfaces. Running the polyimide and stainless back and forth approximately 10-12 times is usually adequate to achieve the required amount of texturing. The main advantage to using this texturing rig is that it allows for uniform pressure, which produces uniform texturing thereby preventing the formation of pin holes which could lead to short circuiting in the transducer during pressure cycling.

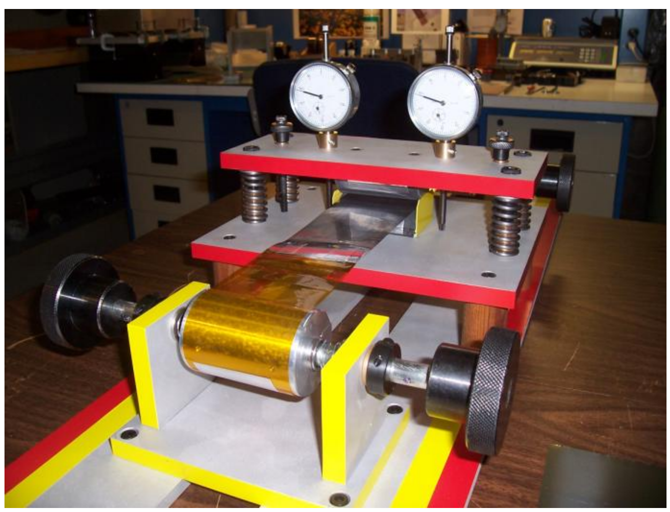

Fig. 1. Texturing Fixture. Polyimide being textured. Notice the dial indicators. The height of the texturing rig is can controlled to maintain a uniform pressure and texture across the width of the transducer.

Electrode cutting

Following texturing, the stainless steel layers are ready to be cut to size. To do this, the stainless steel foils are stacked between copper foils and clamped in place. This is shown in Fig. 2.

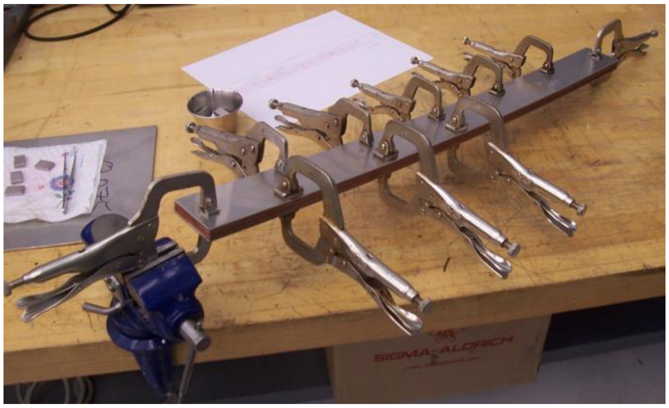

Fig. 2. Stainless Steel and Copper Package. Textured stainless steel and copper foils are stacked and clamped to prepare for EDM cutting.

The ends of the package are then welded together to maintain clamping pressure for cutting. This is done so the package does not spring apart while cutting. Next, the stainless steel and copper package is cut using Electrical Discharge Machining (EDM). The copper foils between the stainless steel foils are required to prevent the stainless steel from welding together from the intense heat of the EDM. This process is efficient because many electrodes are cut simultaneously. Following cutting, the stainless steel electrodes are cleaned with acetone and all edges are de-burred using a steel roller. The de-burring step is important because stray sharp edges could penetrate the polyimide thus causing a short circuit which would destroy the transducer.

Insulator cutting

The polyimide layers are then cut using a razor blade, two templates and a cutting fixture. The two templates are made from stainless steel and are in the shape of the insulating polyimide layers. The polyimide is clamped between the two templates and a razor blade is used to cut around the perimeter of the template. Much care must be taken during cutting, which includes keeping the razor blade a specific angle of approximately 30 degrees, to prevent tearing the polyimide. Because tearing has often occurred along the long straight edge of the template, a cutting fixture has been constructed to allow for a more direct and natural cutting angle. This fixture can be seen in Fig. 3. A new razor blade will be used on each layer.

Fig. 3. Cutting Fixture. These pictures show the cutting fixture alone, cutting fixture and polyimide in its cutting template, and how the template fits into the cutting fixture.

Once the polyimide is cut, all pieces are cleaned with isopropyl and inspected under a microscope to inspect for tears and pin holes. If any pin holes are spotted, the cutting is discarded. Stray edges are also removed using a razor blade. A thorough inspection of the polyimide layers is very important because this provides the main line of defense again transducer failure from short circuiting.

Assembly

The polyimide and stainless steel layers are now ready to be assembled. However, achieving proper alignment requires an assembly fixture. Features that must be included the following: “it must keep each layer aligned; it must bend the nodes of the stainless steel layers so that they meet the specifications of the model magnet; it must provide for the epoxy cure of the transducer” [2].

The alignment and epoxy curing fixture is shown in Fig. 4. The rectangular groove on the center piece provides the surface where the polyimide and stainless steel layers are stacked and bonded. The grooves running to the edge of the fixture provide a route for excess epoxy to be pushed out during the clamping and curing process.

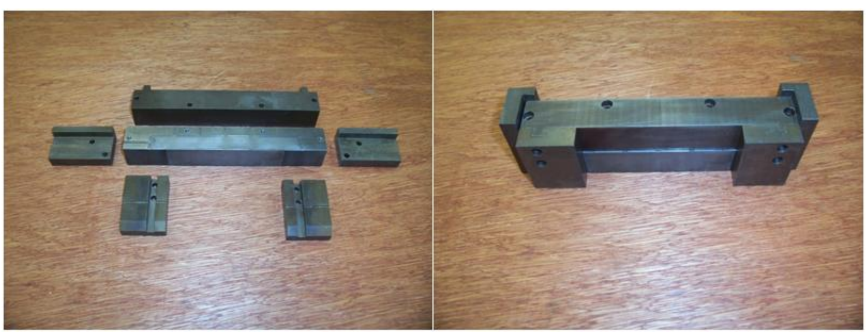

Fig. 4. New Alignment and Epoxy Curing Fixture. These pictures show the fixture fully disassembled and assembled respectively.

Prior to assembly, the surfaces of the fixture are coated with a PTFE mold releasing agent. This allows the transducer to be easily removed once cured. Next, the polyimide and stainless steel layers are stacked alternately with the nodes of the stainless also alternating from left to right. The epoxy used in the process is M-bond 610 epoxy. Epoxy coating should be thin and uniform along each layer and applied using a small brush. Tweezers, spatulas, and magnifying eyewear are recommended as they essential for small adjustments.

Following stacking and epoxy application, using the attachable guide rails shown in Fig. 4, the top of the fixture is placed on the transducer and tightened to 50 in-lbs using a torque wrench while being held by the torque fixture. This setup is shown in Fig. 5. Finally, the two remaining pieces are guided over the exposed stainless steel nodes and tightened. This bends the nodes 90 degrees which is required for the magnet.

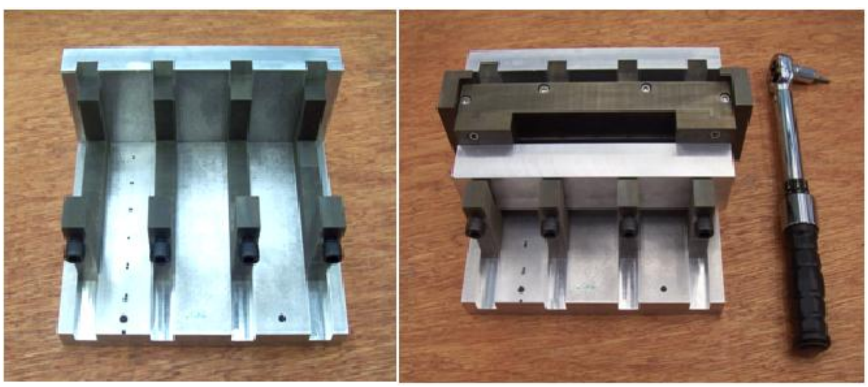

Fig. 5. Torque Fixture. This figure show the torque fixture (Left) and the torque fixture holding the alignment and epoxy curing fixture with the torque wrench resting next to it (Right).

Epoxy curing

The epoxy must be cured in an oven to complete the fabrication process. After curing the alignment and epoxy curing fixture is opened and the transducer is removed. Any residual epoxy must be broken or cut off of the transducer using a razor blade. Acetone is then used to clean the fixture. Care must be taken to remove all remaining epoxy from all fixture faces to prevent residual build up which decreases repeatability. This is done by scraping any remaining epoxy away with a razor blade under a microscope.

Calibration

Calibration is done by applying a known pressure normal to the face of the transducer and tracking the capacitance as a function of pressure. As the pressure on the transducer increases, the insulating polyimide layer is compressed which brings the stainless steel layers closer together. Because capacitance is inversely proportional to the distance between the plates, the capacitance will increase. Using multiple layers is advantageous because it provides a larger surface area which increases the base capacitance. This is important because a typical base capacitance is on the order of 5 nano-farads (nF) and must be measured to a precision of pico-Farads (pF). Also, with more polyimide to compress between the stainless steel layers, there is an increased change in capacitance for a given pressure.

The set up for each calibration test is identical. The first step is to wire the nodes in series. These wires are then connected to a Keithley 3322 LCZ meter which is used to measure capacitance. The transducer is then cleaned with isopropyl and placed in the testing fixture. This fixture is designed to evenly distribute the load across the face of the transducer. The testing fixture is then placed inside a box constructed from thermally insulating G10 material which is then centered in a heavy press. This set up can be seen in Fig. 6. Calibration is done in two stages. These are described below.

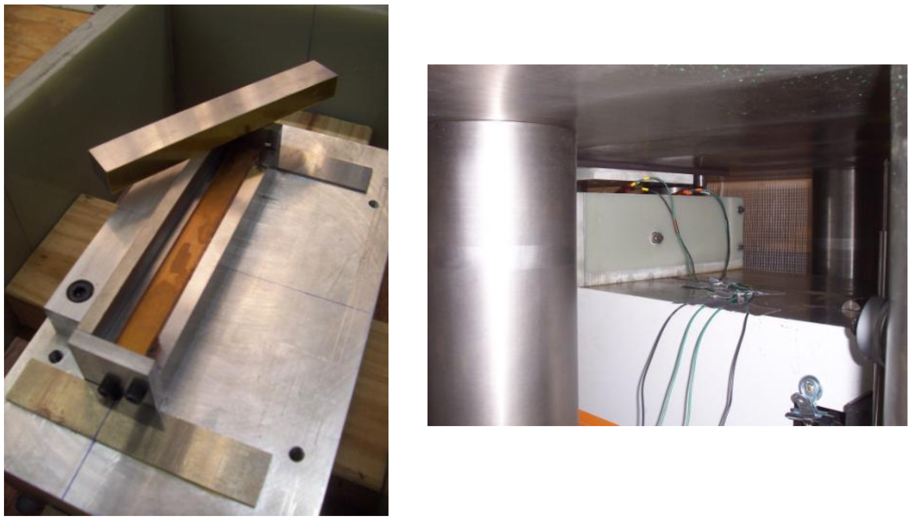

Fig. 6. Calibration Fixture. The outer box is G10 thermally insulating container for liquid nitrogen testing. (Right) Transducer wired, placed in press and ready for testing.

All tests are done either at room temperature (300K) or liquid nitrogen temperature (77K). Testing must be done at 77K to simulate conditions in the magnet. Even though the magnet will operate at much colder temperatures (4.2K), "the mechanical and electrical properties of the polyimide, stainless steel and epoxy vary much more dramatically in the transition from 300K to 77K than from 77K to 4.2K" [2].

Calibration stage 1: pre-magnet epoxy curing cycle

The first calibration stage is composed of two sets of calibration tests. The first set is done at room temperature while the second set is done at 77K. For the room temperature test, the transducer is loaded from 0 – 5000 pounds per square inch (psi) in increments of

100 psi for 0-600 psi and 500 psi for 1000-5000 psi. This is done 5 times. To ensure the capacitance has settled out before the next reading is taken, the capacitance will be monitored for 30 seconds with the stable value recorded. The second set of tests are conducted at 77K by filling the G10 box with liquid nitrogen and allowing the transducer to reach near thermal equilibrium with the liquid nitrogen. Because G10 is a cryogenically rated insulator, the volume of liquid nitrogen consumed during this test is minimized. To help automate the test, nitrogen levels are held constant using an auto fill sensor. This set up can be seen in Fig. 7. The transducer is cycled 3 times using the same measurement and loading procedure described for the room temperature test. Calibration curves are then constructed by plotting pressure versus capacitance.

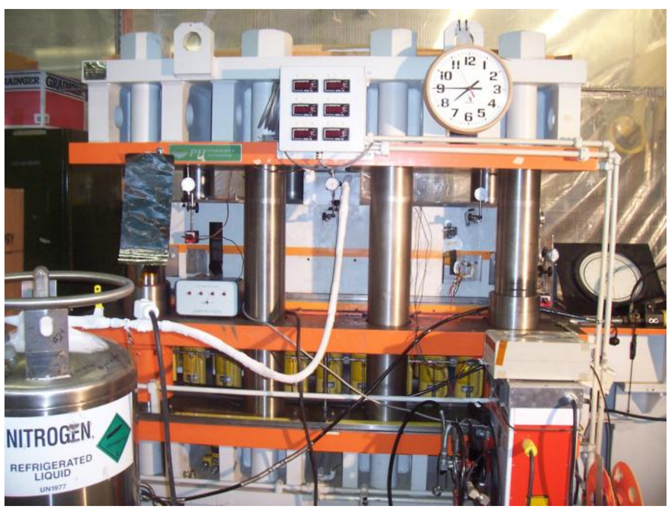

Fig. 7. Liquid Nitrogen Calibration Setup. Notice the iced liquid nitrogen cylinder feeding the G10 test box. The liquid nitrogen level is maintained by the auto fill controller to the right of the nitrogen cylinder.

Calibration stage 2: post magnet epoxy curing cycle

Following completion of the first calibration stage, the transducers are placed back in their alignment and epoxy curing fixture and put through the magnet epoxy curing cycle.

As stated earlier, this simulates the magnet's curing cycle once installed in the magnet. Temperatures for this cycle near the melting point of the epoxy used in the transducers which causes an unpredictable calibration curve zero offset which effectively erases all previous pressuring trainings from calibration stage one. A motivation for this test is to see if increased repeatability of transducer fabrication has affected the consistency of the zero offset.

Following the magnet's epoxy curing cycle, the testing procedure described in the first calibration stage is repeated. Measurements are then plotted and compared.

CHAPTER III

RESULTS

Results are presented in a similar fashion given in Chapter II.

Fabrication

The following section is devoted to describing the effectiveness of methods and tooling used in the construction phase. Comments on the performance as well as problems and changes to the process will be given.

Polyimide and stainless steel texturing

The texturing fixture developed by Ragland worked very well. Previously, the stainless steel and polyimide layers were textured by hand using sandpaper after they were cut to size. Due to uneven pressure and cumbersome clamping techniques, tearing and pin holes would often appear thus potentially causing short circuits within the transducers. Using this texturing device, I only encountered one pinhole throughout this project. Within the scope of this project, a near 100% polyimide acceptance rate should be considered a great success. Also, the rate at which materials may be textured far surpasses older methods. Use of this device is clearly a strong improvement.

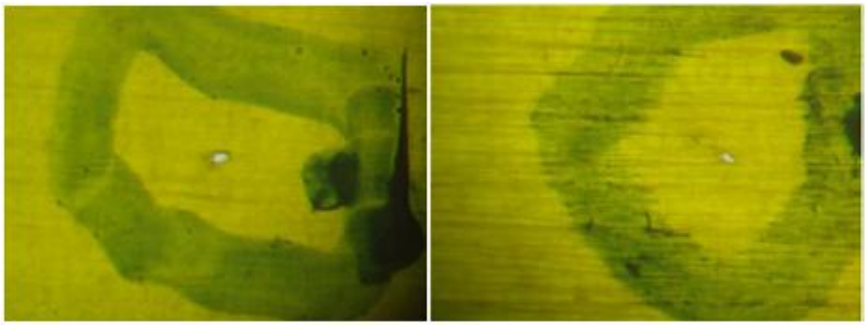

Fig. 8. Polyimide Layer Tearing. These are pictures of .001" thick polyimide after an abrasion-by-hand test, magnified 30x. Notice the small tears in theses layers. The texturing fixture developed by Ragland greatly diminished the frequency of these "pinholes" [2].

Electrode cutting

Since Ragland's research no changes have been made to this part of the process. The EDM does a remarkable job cutting the stainless steel electrodes. However because a large amount stainless steel electrodes were cut during Ragland's research, the majority of them were not cleaned thoroughly. This resulted in stains, similar in appearance to water stains, across the surface of the stainless steel electrodes. The stains were most likely caused by residual liquid left over from the EDM cutting process. Even though these stains were not a major problem, care was taken using fine grit sandpaper (1200 grit) to sand the stains off as best as possible followed by a cleaning with acetone. This was done to ensure there were no residual chemicals that could affect the epoxy bonding. After cleaning, the pieces with the least amount of staining were selected for the transducers.

Insulator cutting

The new cutting fixture worked very well. As seen in Fig. 3, the cutting fixture allows for a surface for the razor blade to press against an aluminum surface during cutting.

This allows the user to apply additional pressure during cutting which reduces risk of tearing. Pieces cut with this fixture have been thoroughly inspected and are acceptable. Because this fixture simplifies cutting, it has also increased the cutting rate. We are now able to cut the required polyimide layers for 2 transducers in about 4 hours compared to 5.5 hours without the cutting fixture.

Assembly

When compared to all of the other processes, the assembly and epoxy curing process has the largest potential for problems. Because the transducers are assembled by hand, there is a large margin for error. However, the new alignment and epoxy curing fixture makes this step much easier. It houses many features that the old alignment and epoxy curing fixture did not contain. Fig. 9 below shows pictures of both fixtures which makes comparison easy.

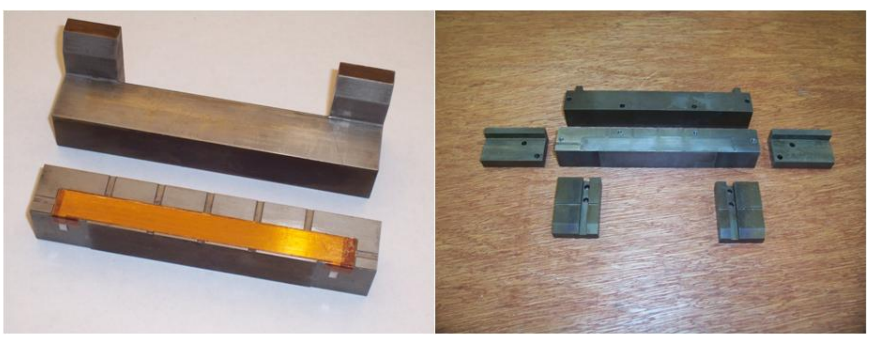

Fig. 9. Old and New Alignment and Epoxy Curing Fixtures. This figure shows the old and new alignment and epoxy curing fixtures. One can see that the new alignment and epoxy curing fixture contains many more pieces which help control variables during assembly.

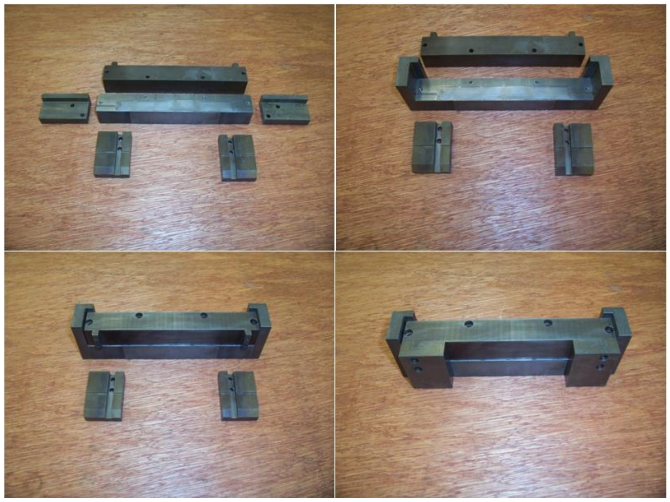

Fig 10. Assembly of Alignment and Epoxy Curing Fixture. This series of pictures shows how the new alignment and epoxy curing fixture fits together.

From Fig. 9, one can see that the old fixture was only made of 2 pieces. The ears on the top piece were used to bend the leads 90 degree. However, the transverse motion required to put the fixture together introduces the risk of misaligning the freshly assembled package. This causes inconsistencies from transducer to transducer. With the new fixture, we have eliminated this problem. As seen in Fig. 10, the two side pieces act as guides for the top large piece as it is brought directly down on the transducer. Once the top piece is bolted in place, the remaining front two feet are then guided over the exposed leads to bend them 90 degrees.

While the new fixture provides much more control during clamping and curing, problems are still encountered during the alignment process. The step is especially difficult because alignment is done by hand. To ease this process, tweezers, spatulas and a magnifying loop are used to ensure each layers is aligned as close as possible. To prevent the first layer from shifting, a small amount of epoxy is applied to bond the first polyimide layer to the fixture. If the layers are misaligned at any point during stacking, it must be peeled back and readjusted. This is risky because each time a layer is adjusted, it is probable preceding layers will also be shifted. Once the polyimide and stainless layer are in place, a spatula is swept across the surface to ensure all isolated air bubbles are pushed out.

During the tightening process, we were not able to use a torque wrench because it was not available during the production of our transducers. Using an Allen wrench, we tightened the fixture down to what felt to be the same. Even though we were not able to use a torque wrench, the transducer's thickness was even more uniform that what had been previously achieved. For our next set of transducers, we will use a torque wrench to tighten all of the bolts to 50 in-lbs and use the torque fixture to ensure each bolt receives the same amount of tightening.

Following epoxy curing, the transducer was easy to remove from the fixture. Even though we had coated epoxy on the bottom surface of the fixture, because we had applied the mold releasing agent, the transducer was easily removed from the fixture. Following removal, both fixtures were cleaned thoroughly with a razor blade under a microscope to remove any residual epoxy.

Overall, use of the alignment and epoxy curing fixture has produced impressive results. Across the length of the transducer, Ragland's thickness varied up to 0.0008" where ours only varies by 0.0002”. This is a 75% decrease in thickness variation. This improvement is most likely a result of ability to control epoxy thickness and distribution enabled by using the new alignment and epoxy curing fixture.

We are also able to significantly reduce the total epoxy thickness. It is important to note that that Ragland’s designed transducer thickness, not including for epoxy, was 0.017” while ours is 0.013”. Ragland’s maximum total epoxy thickness was 0.0042” while ours was 0.0016”. Comparing these two maximum values, it is clear we are reducing the maximum epoxy thickness by over 62%. A reduction in epoxy means the stainless steel layers are closer together thus resulting in a larger base capacitance. It also allows more compression of polyimide which results in a greater gauge sensitivity. From these results, it is clear that new fabrication tooling has a positive effect on the dimensional characteristics of our transducers.

Calibration

The steps taken to calibrate our transducers have resulted in many interesting results. These are described in detail below.

Calibration issues and solutions

Throughout the calibration process, we overcame many obstacles. One important problem solved was wiring optimization and consistency. Because the leads of the transducers are very fragile, we quickly found out that the leads must be soldered to the transducer in order to ensure the connection would not disconnect during testing. Each connection was covered by heat shrink tube for additional protection and stress relieving. It was also determined a consistent wiring set up is required for every test because the measured capacitances are on the order of picofarads (pF). Consistent wiring is important because different wiring arrangements may offset measurements by several pF thus skewing calibration. The wiring set up is shown in Fig. 11.

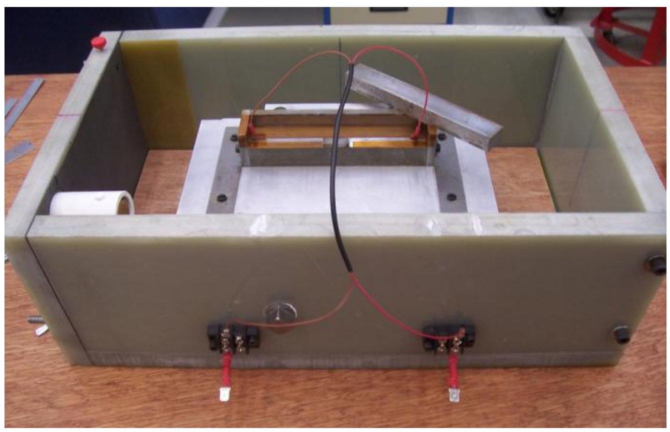

Fig. 11. Wiring Improvements. Shows wiring improvements made to transducer and testing fixture. Allows for consistent wiring from test to test.

Another problem overcame while developing the calibration process was our inability to see the press make contact with testing fixture. This is because the G10 box walls are higher than the transducer fixture. Knowing when the press and testing fixture are in contact is important because we need to know what our gauge pressure (press pressure) zero is. To solve this problem, a 0.001” stainless steel shim, wider than the width of the testing fixture, was inserted between the testing fixture and the press. The press was then brought closer to the fixture until the shim could no longer slide between the press and the testing fixture. This point defines the gauge pressure zero. Dial indicators with a resolution of 0.0005” were also used to track the height of the press during calibration.

Pressure cycles: pre-magnet epoxy curing cycle

Figs. 12 and 13 show a set of stage one (pre-magnet epoxy curing cycle) calibration curves for transducers 1 and 2. These display the calibration curve convergence over a series of 3 pressure cycles. It is easy to see the change between each test is small thus hinting a quickly converging behavior.

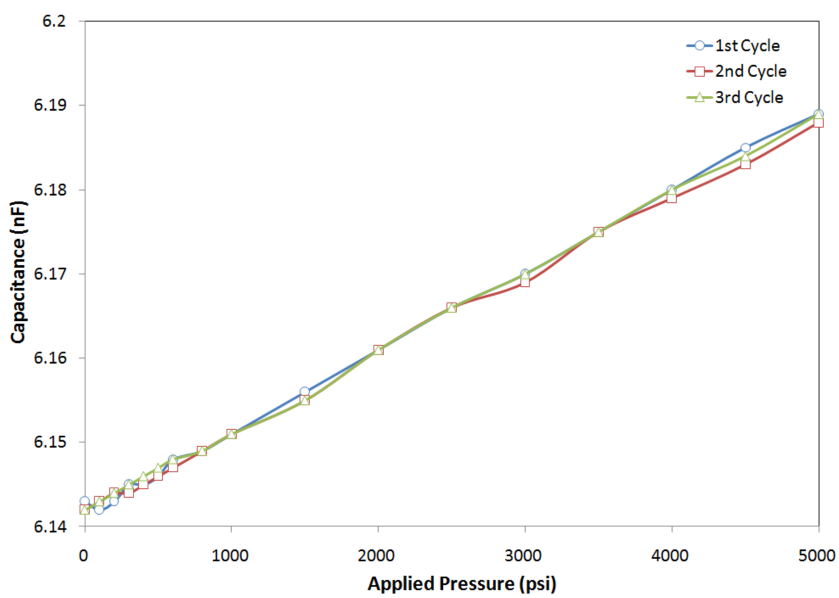

Fig. 12 Stage 1 Calibration for Transducer 1. The difference between each pressure cycle is very small. This results in a fast convergence rate.

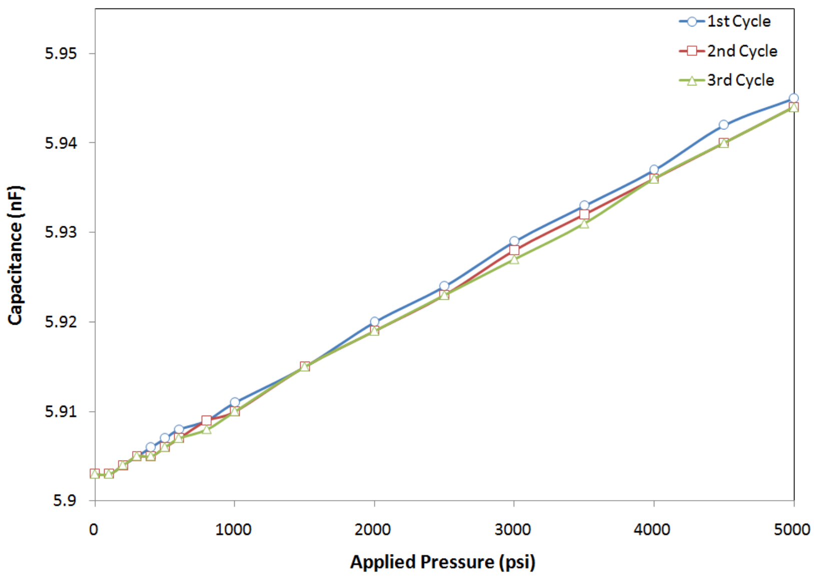

Fig. 13. Stage 1 Calibration for Transducer 2. As with transducer 1, the differences between pressure cycles are very small.

We now plot the absolute value of the change in capacitance for a given pressure from the 1st to 2nd and 2nd to 3rd pressure cycle. Figs. 14 and 15 show this for transducers 1 and 2 respectively.

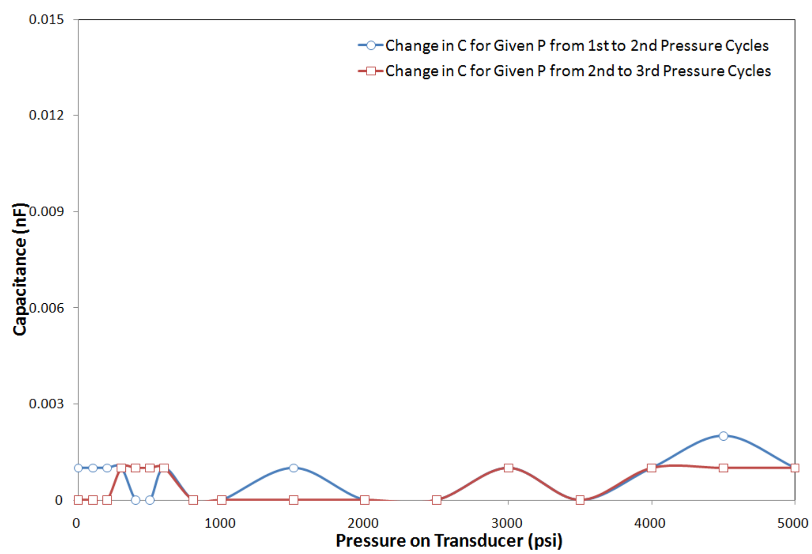

Fig. 14. Change in C. for Given P. for Transducer 1. The absolute value of the change in capacitance between pressure cycles is very small. By the 3rd pressure cycle the capacitance difference jumps around 1 pF. This is the resolution of our meter.

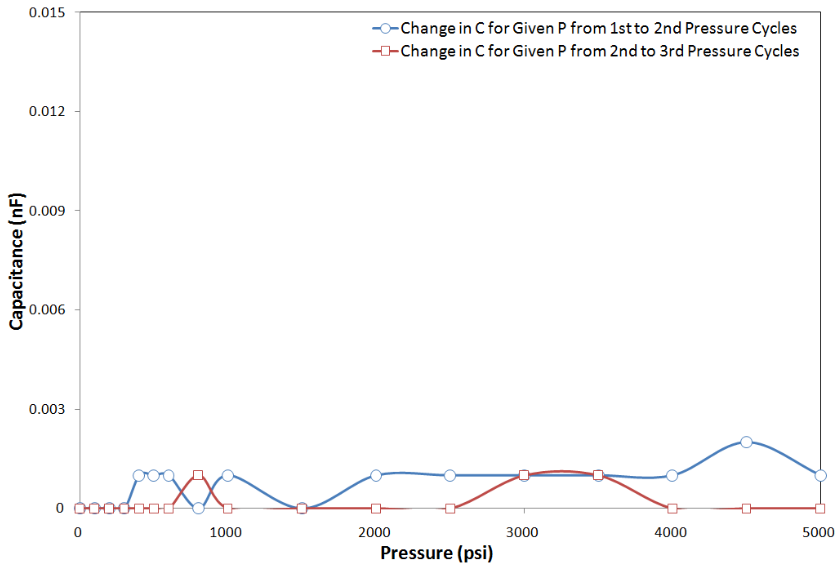

Fig. 15. Change in C. for Given P. for Transducer 2. The absolute value of the change in capacitance between pressure cycles is very small. By the 3rd pressure cycle the capacitance difference jumps around 1 pF. This is the resolution of our LCZ meter.

To quantify our improvements, we now compare our results with Ragland's. His change in capacitance for a given pressure can be seen in Fig. 16.

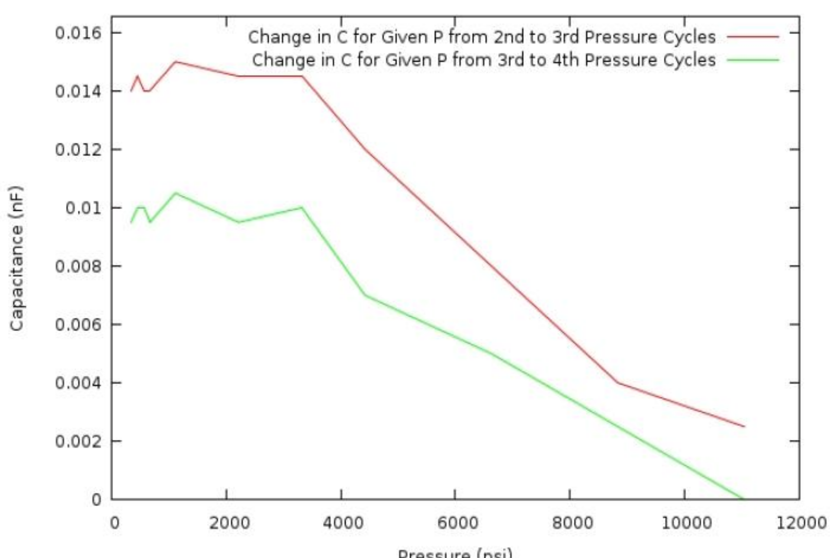

Fig. 16. Ragland's Change in C. for a Given P. Notice that from 2nd to 3rd pressure cycle, at 4000 psi, there is a change in C of approximately 14 pF, where in our data the change was negligible.

It is clear that we are able to dramatically reduce the change in capacitance for a give pressure over the span of 3 pressure cycles. For transducers 1 and 2, we are able to reach a change in capacitance that is within the resolution of our LCZ meter by the 3rd pressure cycle. However, Ragland's transducers were projected to reach a "negligible [change] near the 10th pressure cycle" [2]. Remarkably, this is a 70% decrease in the number of cycles required for convergence.

Pressure cycles: post magnet epoxy curing cycle

As expected, the capacitance zero shifts once the transducer is put though a magnet epoxy curing cycle. The zero offset resulting from the magnet epoxy curing cycle for transducer 2 was -0.109 nF. This number is fairly small. In an effort to try and replicate this zero offset, we transducer 1 will be put through the same magnet epoxy curing cycle. Transducer 1 has not been though the magnet epoxy curing cycle because stage one testing has not been completed due to lead connectivity problems. Once these problems are resolved it will be put though the magnet epoxy curing process and provide another offset to which we can compare transducer 2.

Following stage two pressure testing, it was observed that the convergence behavior seen in stage one testing was conserved. Fig. 17 shows the convergence of the calibration curves for 3 pressure cycles. For these tests, the bottom, linear curve represents applying pressure while the top represents removing pressure. For tests 1 through 3, pressure was completely removed at the end of the cycle and reset to zero. This allowed the capacitance zero to jump back to its zero for the next test. However, for tests 4 and 5, shown in Fig. 18, testing began and ended at 200 psi. This was to simulate the loading conditions in the magnet. Notice the curves form a closed hysteresis curve by the 5th pressure cycle. This means the transducer has reached a fully calibrated state.

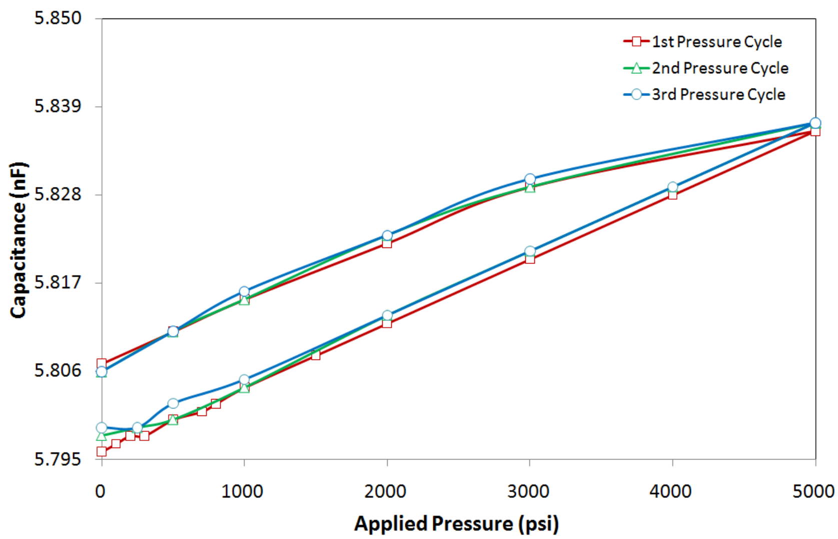

Fig. 17. Stage 2 Calibration Tests for Transducer 2. The difference between each pressure cycle is very small. This results in a fast convergence rate.

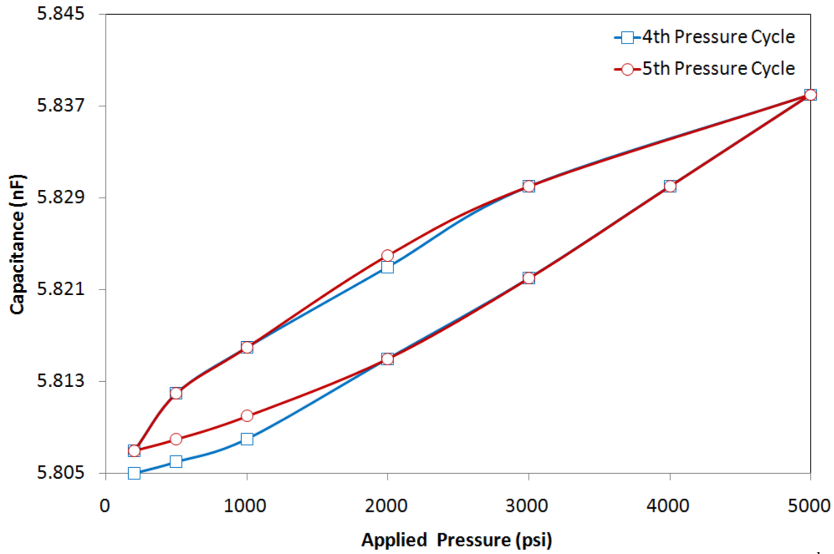

Fig 18. Stage 2 Calibration Tests for Transducer 2, Cycles 4 and 5. It is clear that by the 5th pressure cycle that the calibration curve has completely converged forming a closed hysteresis curve.

It is clear from Figs. 17 and 18 that the quickly converging behaviors are conserved. Also, Fig. 18 shows that complete convergence has been achieved by the 5th pressure cycle. This is because the calibration hysteresis curve completely traces itself by the 5th pressure cycle.

As shown in the previous section, by plotting the absolute value of the difference between pressure cycles, we can look at the change in capacitance for a given pressure between pressure cycles. To show the convergence behavior is similar to the stage 1 calibration tests, Fig. 19 shows the change in capacitance for a given P for Fig. 17.

Fig. 19. Stage 2 Change in C. for Given P. for Transducer 2. It is clear that by the 3rd pressure cycle, the curves have converged within the resolution of our LCZ meter.

We also confirmed that there is a negligible time constant associated with the compression of the polyimide. This was done by taking three capacitance measurements over the duration of 2 minutes to see if the capacitance was time dependent. It was concluded that there was no time dependence. Therefore, the rate at which pressure may be applied to the transducer without skewing the behavior are within the bounds established during Ragland's research (4.4 psi/sec).

Overall, it is clear that the convergence rate has not been affected by the magnet epoxy curing cycle. This is a very important result as it allows for the transducers to be re-calibrated within three to five pressure cycles within the magnet.

CHAPTER IV

SUMMARY AND CONCLUSIONS

The goal of producing a set of repeatable and reliable capacitive stress transducers has not yet been accomplished. However, many remarkable improvements have been made to the fabrication and calibration processes. Complete conclusions are unable to be drawn because we have only produced a set of 2 transducers, where one has not completed both calibration stages. However, we can comment on the data presented thus far and interpret how it is affecting the repeatability of the gauges.

The incorporation of the cutting, torque and alignment and epoxy curing fixture into the fabrication process has clearly had an effect on the thickness variation of the transducers which in turn affected the calibration convergence rate. The ability of the alignment and epoxy curing fixture to decrease the thickness variation across the length of the transducer by 75% while reducing the total epoxy thickness by over 62% clearly means we have been able to control variables in the stacking and bonding process that were previously left unchecked. Because the total epoxy thickness has been reduced, the compression of the package is concentrated more in the polyimide. This means less "fluff" needs to be compressed within the epoxy which leads to a faster calibration curve convergence rate. Because the stainless steel layers are closer together this also implies an increase base capacitance. Also, less epoxy, which has a higher modulus than polyimide, means greater deflection per unit force which increases the sensitivity of the gauge. Both of these are helpful because we are measuring capacitance changes on the order of picofarads.

While our thickness variation as been greatly reduced, there is still room for improvement. Because a brush was used to apply the epoxy during the stacking process, it is likely that the epoxy is not uniformly distributed across the layer. If a new technique, such as spaying the epoxy, could be developed, this would reduce any risk of non-uniform epoxy thickness thereby increasing transducer reproducibility. Another improvement that could be made during the construction process would be a guide which would allow a controlled amount of polyimide or stainless to be placed on the package at one time. Previously, the loose end of the polyimide or stainless rested on spare hand tools while the other end was aligned. If this new fixture were constructed, any risk of the new layer touching the package causing misalignment would be eliminated.

The calibration of the transducers is now better understood. For all tests, the calibration data suggested that the calibration curves converge to the resolution of our LCZ meter (1 pF) within 3 pressure cycles and completely trace themselves by 5 pressure cycles. This is a remarkable improvement compared to previously requiring 10 pressure cycles for the same convergence. This means the transducers will be calibrated well before completion of the magnet pressure training.

Although we do not have sufficient data to comment on the consistency of the magnet epoxy curing cycle base capacitance zero offset, because the change in capacitance between the first and second cycles of stage two calibration testing were small, if the zero offset is not consistent, we are able to measure the deflection of the laminar spring (which are used to maintain preloading on the coil windings at all times) which will give us the initial pressure on the transducer. Because calibration curve will fully converge within three pressure cycles, recalibration of the gauge following installation the magnet will should be straightforward. However, if the zero offset proves to be consistent, recalibration will be even simpler.

Overall these results point to a hopeful future of integrating repeatable and reliable transducers within our model dipole magnets. This research has been one of many steps working towards this goal. Future work includes producing a new set of transducers to see if these results are repeated. Next, another set of transducers will be made during the summer of 2010 which will be used in the model dipole magnet TAMU III.

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